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Comparison of coupled and uncoupled load simulations on a jacket support structure

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Abstract

In this article, a comparison of the moments and forces at the joints of a jacket structure is made between fully coupled aero-hydro-elastic simulations in HAWC2 and uncoupled load predictions in the finite element software Abaqus. The jacket sub structure is modelled in moderate deep waters of 50m and designed for the 5MW NREL baseline wind turbine. External conditions are based on wind and wave joint distribution for a site in the North Sea. The turbulent wind field in HAWC2 is generated by random values, defined by the Mann Turbulence model, for each operational mean wind speed. A four-legged jacket structure similar to the Upwind reference jacket is developed in the Abaqus environment, to which is added the transition piece and tower. The aeroelastic loads determined in normal operating conditions of the turbine is integrated and centralized as nodal forces and moments acting at the tower top of the finite element model. Hydrodynamic loads from the incoming waves are computed using the Morison equation and based on a nonlinear irregular wave field. Velocities, accelerations and amplitudes of the wave field as well as tower top forces and moments are used as inputs for the structural analysis in Abaqus. The fully coupled simulation is implemented and performed in HAWC2. In the uncoupled case, the loads (wave loads and tower base loads) are analysed by an implicit structural Finite Element Analysis (Abaqus 6.11-1). A subroutine is used as a preprocessor generating a beam element model and linking the loads to the components as nodal forces. In both simulation cases, the integrated loads acting on the jacket legs are computed as time series and as damage equivalent loading. The analysis and comparison of the fully coupled and decoupled simulation method show that the results vary depending on the structural stiffness and the applied wave loads. Variation in the amplitudes of the moments and forces on the jacket legs up to 25% was observed between the results obtained from coupled and uncoupled simulations.

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Nomenclature

C_D	drag coefficient
C_M	inertia coefficient
D	diameter
F	forces
H_s	significant wave height
Hz	Hertz
m	meter
s	second
T_p	peak spectral wave period
t	time
u	velocity
\dot{u}	acceleration
ρ	density

1. Introduction

Offshore wind turbine installations are moving beyond shallow water depths with less than 25m to moderate water depths between 35m to 60m [1]. Most sub structure designs being currently installed at such moderately deep waters are fixed base frame structures such as jackets and other multiple pile structures such as Tripods. Different fixed based sub structure concepts with innovative designs are proposed in the UpWind project final report [2, 3]. The sub structure must resist the mechanical loading from the wind turbine rotor and the hydrodynamic excitation from the waves, which sets these designs apart from offshore oil rigs, which have primarily only wave excitation. The wind loads from the rotor can cause design challenges on the support structure such as fatigue damage especially within a wind farm due to the wake from surrounding turbines or when the wind and wave directions are not coincident. Further the rotor loads being extremely dynamic result in significant vibration of the sub structure and fatigue of the joints connecting the frame members.

The design of offshore wind turbine structures is based on computer simulations of various load cases that the turbine is expected to experience in its life time as stipulated in the IEC 61400-3 standard [4]. The computation of the loads on the sub structure based on these design load cases requires fully coupled aero-hydro-elastic simulations. However on many occasions, the turbine design is made by a manufacturer and the sub structure (such as a jacket) design is made at another company and it is often not possible to have a fully integrated model in a simulation platform. It is then imperative to understand the difference in sub structure internal forces and moments from those obtained in fully coupled load simulations against those determined using uncoupled load simulations where the tower top loads from the rotor are captured using an aeroelastic software and then used in a different software in which the tower, transition piece and sub structure are represented. Herein the tower, transition piece and jacket structure of the UpWind 5MW turbine [5] are modeled in the Abaqus [6] platform. The hydrodynamic loads are input to Abaqus using a Matlab based code that uses the Morison equation [7] based on wave kinematics obtained using a second order nonlinear irregular wave model. The tower top fore-aft and side to side forces and bending moments are input to the Abaqus model based on normal turbulent wind simulations conducted in the HAWC2 aeroelastic software [8, 9, 10] between 8m/s and 25m/s mean wind speeds.

2. Basic model

The UpWind /NREL 5MW wind turbine has been used in various offshore wind turbine loads simulations and its configuration details are described in length in Ref. [5, 11]. The HAWC2 model of the

wind turbine is comprised of multi-body finite elements assembled to satisfy the kinematic constraints at the interfaces between the bodies. The turbine controller is developed at DTU and possesses symmetric blade pitch control and variable speed generator control. The HAWC2 model and simulation results from HAWC2 on a wide range of offshore support structures is presented in the offshore code comparison exercise [11]. The wind turbulence is represented using the Mann model [12] and 6 Gaussian ten minute wind realizations are simulated at every mean wind speed from 8m/s to 25m/s. The turbine is run under normal operation. The blade representation in HAWC2 is aeroelastically coupled to the wind field using unsteady aerodynamics. The support structure loading is coupled to the motion of the sub structure using the Morison equation that incorporates the kinematics of the support structure and its orientation during the computation of the marine loading. The wave kinematics is developed using second order irregular nonlinear waves, where the wave height is based on a JONSWAP spectrum. The jacket structure is modeled in HAWC2 using Timoshenko beam elements and a rigid soil interface is considered. The wave loads impact all members of the jacket and shielding effects are not considered.

2.1. Uncoupled model implemented in Abaqus

The uncoupled model is implemented in the commercial structural Finite Element Analysis tool Abaqus Version 6.11. The jacket model consists of Euler-Bernoulli beam elements. The beam cross-sections are defined according to the described model in the "UpWind reference jacket" [13]. Rotary inertia of the beam cross sections in bending is ignored.

The rotor nacelle assembly (RNA) including the hub is modelled as rigid bodies where masses are lumped together according to the NREL 5-MW baseline turbine. The transition piece (TP) between the baseline turbine and the jacket structure is modelled as a rigid body, where the 600 tons dead load of the TP are assumed as a density filling a rectangular body with the dimensions of 9.6m (length) x 9.6m (width) x 4m (height). The entire model consists of tower top mass, tower, TP, jacket structure and a circular foundation (monopile below the mudline). All parts are connected via kinematic coupling constraints.

The loads are applied at the nodes of the jacket structure. The loads are analysed with an implicit, linear solver for dynamic simulations, wherein the time step is adjusted to confirm to numerical stability at all time. The tower top loads (forces and moments in y- and x-direction) are applied at the intersection between the rigid RNA and the tower top node at a height of 88.15m. The waves are assumed to be collinear with the wind direction and impact the jacket structure at all members.

2.1.1. Particular variations of the Abaqus model

In the Abaqus model, the jacket support structure possesses kinematic coupling constraints connected to a cylindrical annulus at the mudline level. All six degrees of freedom of the jacket legs at the base are coupled to the annulus. The annulus is fully clamped at one meter below the mudline, meaning that all degrees of freedom are set to zero therein as depicted in Figure 1. The blue rendered part of the piles in Fig. 1. above the mudline consists typically of two tubular members, the piles (anchoring elements) and the jacket legs (sleeves). The connection between the sleeves and the piles is filled with grout material. The stiffness of the steel sleeves and the jacket legs in combination with the grout material is very high. Therefore in the Abaqus simulation the connection was simplified and is assumed to be a rigid connection. Marine growth is not considered in the model and, neither are flooded jacket members.

3. Natural frequency comparison

In order to verify the structural representation of both models (HAWC2 and Abaqus model) are identical, along with their geometrical consistency, the natural frequencies of the jacket structure are compared. The natural frequency of the coupled structure is displayed in Table 1, wherein it is seen that the structural frequencies in both software match quite well for the first and second fore-aft modes

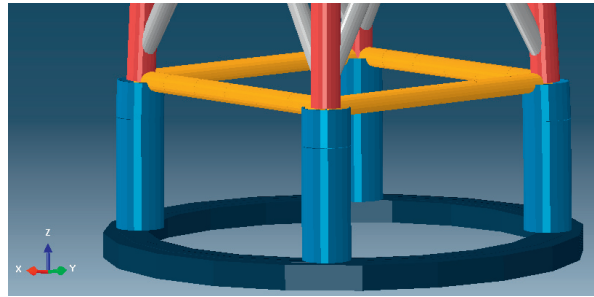


Fig. 1. Sketch of the analysed jacket structure and its boundary conditions at the mudline.

and side-side modes (see Table 1). Figures 2 and 3 show the corresponding eigenmodes of the natural frequencies. Deviations between the HAWC2 and Abaqus mode shapes and frequencies are minor. The maximum deviation is in the order of 1.25% between both simulations. The reason for this deviation could be that for the uncoupled representation, the rotor blades, the nacelle and the hub are substituted by added point masses. This point masses are placed according to turbine defined in Ref. [13].

Table 1. Natural frequencies of the jacket structures

Mode	Abaqus model	HAWC2 model
1 st Fore-Aft Mode	0.3169Hz	0.3164Hz
1 st Side-Side Mode	0.3174Hz	0.3214Hz
2 nd Fore-Aft Mode	1.2090Hz	1.2047Hz
2 nd Side-Side Mode	1.2145Hz	1.2144Hz



Fig. 2. (a) 1st Fore-Aft Mode; (b) 1st Side-Side Mode; (c) 2nd Fore-Aft Mode; (d) 2nd Side-Side Mode. Eigenmodes of the jacket structures modelled with Abaqus.

4. Load calculation

Wind and waves are aligned in all load simulations performed. The DLC 1.1 [4] load case simulation results are obtained in HAWC2. In the uncoupled model developed in Abaqus a prescribed loads based approach is used instead of a deformation superposition approach e.g. used by Seidel et. [14]. The internal forces and moments from the fully coupled approach recorded at the tower top are applied

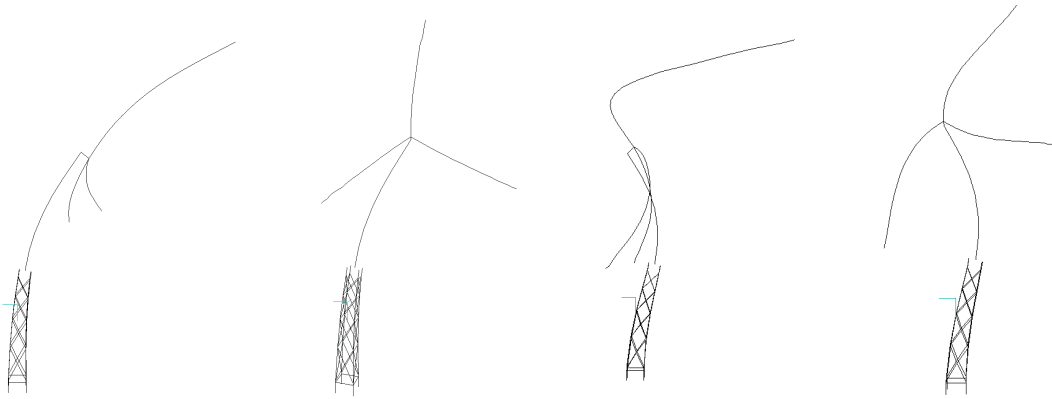


Fig. 3. (a) 1st Fore-Aft Mode; (b) 1st Side-Side Mode; (c) 2nd Fore-Aft Mode; (d) 2nd Side-Side Mode. Eigenmodes of the jacket structures modelled with HAWC2.

together with hydrodynamic loads to the decoupled Abaqus model. However, the forces and moments extracted at the tower top of the fully coupled analysis include any effects due to the hydrodynamic loads. Further the inertial forces on the support structure due to tower deformation are included in both the uncoupled structural analysis and the tower top loads obtained from HAWC2 simulations, which may lead to a conservative tower response.

4.1. Hydrodynamics - wave loads

The wave loads are based on an irregular sea state for the North Sea. The random wave process is defined by the Jonswap spectrum with the significant wave height H_s (see Table 2) at each mean wind speed and peak crossing period TP. The piles and braces of the jacket structure are slender cylinders and therefore the hydrodynamic loads are calculated with the Morisons equation (Equation 1). Standard values for the inertia ($C_M = 2$) and drag ($C_D = 0.9$) coefficients are used. The waves around the structure are assumed to be not affected by the structure itself. The stochastic wave time series at each mean wind speed consists of one random seed and a simulation time of 3600 seconds, which is equivalent to the duration of 6 different wind turbulent seeds. For wave loads, only the immersed part of the sub-structure is subjected to combined drag and inertia forces.

$$F(t) = \frac{\pi}{4} \cdot \rho \cdot C_M \cdot D^2 \cdot \dot{u}(t) + \frac{1}{2} \cdot \rho \cdot C_D \cdot D \cdot u(t)|u(t)| \quad (1)$$

The use of second order non linear random wave representation can result in the instantaneous wave heights to differ from that of a Gaussian wave process, due to the third and fourth stochastic moments being non negligible. The wave surface boundary conditions are satisfied to the second order at each time step, consequently no geometric stretching methods are utilized. This implies that the hydrodynamic loads on the jacket structure can be represented from the wave crest to the mud level at each time step.

4.2. Particular variations of the uncoupled model for the wave load calculation

For the uncoupled model implemented in Abaqus the wave loads are pre-calculated with a Matlab routine for each pile/brace based on the water velocities, accelerations and wave height as well as pile and brace diameter. Phase angle shifts in the wave process between the leading and the tailing jacket structure elements are ignored.

Table 2. Peak spectral wave period and significant wave height

Wind speed	Peak spectral wave period (T_p)	Significant wave height
10m/s	8.02s	4.10m
11m/s	8.53s	4.64m
12m/s	8.92s	5.07m
13m/s	9.15s	5.34m
14m/s	9.74s	6.05m
15m/s	10.21s	6.65m
16m/s	10.56s	7.11m
17m/s	10.72s	7.34m
18m/s	10.86s	7.52m
19m/s	10.99s	7.70m
20m/s	11.12s	7.88m
21m/s	11.24s	8.06m
22m/s	11.37s	8.24m
23m/s	11.50s	8.44m
24m/s	11.63s	8.63m
25m/s	11.79s	8.87m

5. Investigation of tower top displacement

In order to understand the difference in behavior of both models to the represented inputs, the tower top displacement at a height of 88.15m (position of the yaw bearing) was studied. A constant wind speed of 10m/s was simulated and hydrodynamic loads were ignored. The blades were assumed to be rigid in HAWC2 to minimize the aeroelastic effects in the fully coupled simulation. Thus the tower top displacements between HAWC2 and Abaqus are expected to reasonably match with each other since the blades are rigid and the wind input is steady. As seen in Fig. 4, the tower top displacement differed by 1.5% between the fully coupled and de-coupled simulation results, which indicates both model representations are similar without aeroelastic coupling.

Subsequently, the blades were made elastic and a turbulent wind input a mean wind speed of 10m/s was applied in the HAWC2 model. The resulting tower top loads obtained from HAWC2 was applied on the Abaqus model. The comparison of the tower top displacement in x- and y-direction showed slightly differences as depicted in Fig. 5. The tower top displacement in x- and y-direction for the decoupled simulation exceeded the fully-coupled simulation by around 14% (see Fig. 5). The aeroelasticity of the blades requires a coupled analysis, in the absence of which results in the depicted differences in tower top displacements. At higher mean wind speeds, the differences in tower top displacements are expected to be nearly similar.

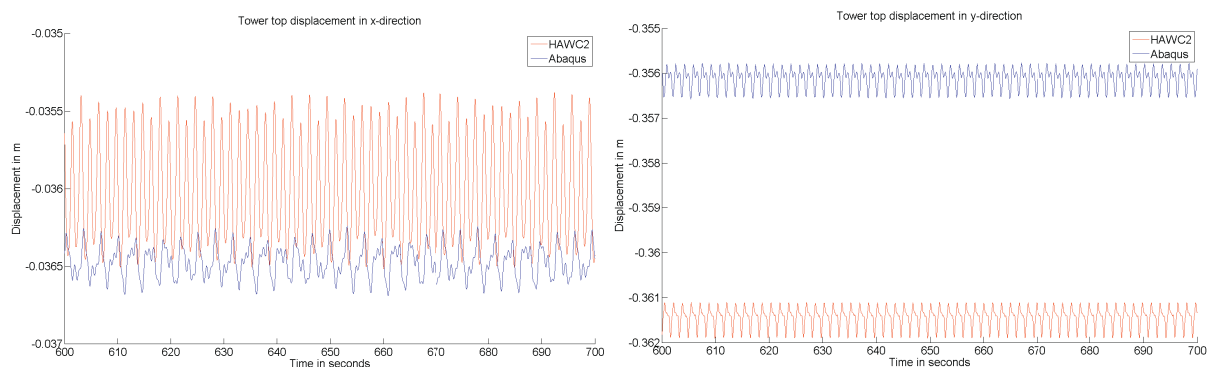


Fig. 4. "Rigid blade"-scenario.

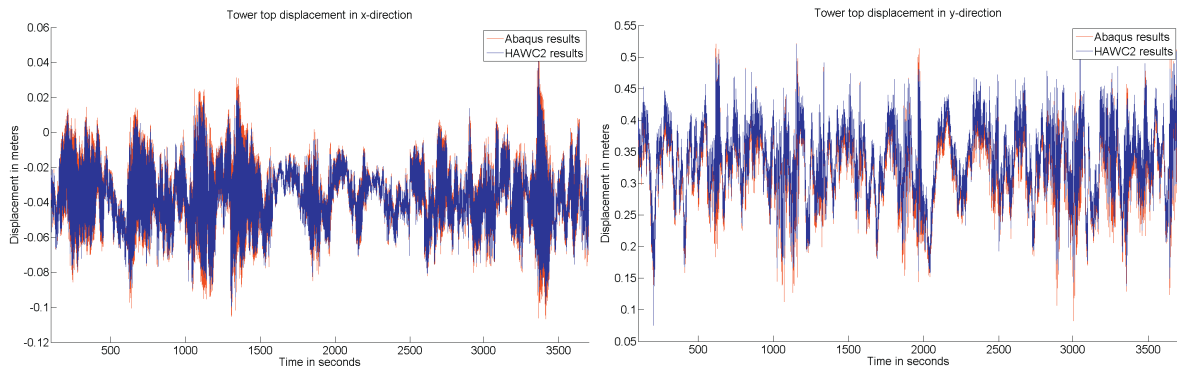


Fig. 5. Turbulent loading scenario with flexible rotor blades.

5.1. Forces at the connection points of the jacket structure

It is required to determine what impact the rotor aero elasticity and the support structure hydro elasticity, which are not represented in the Abaqus model has on the jacket leg loads. In order to answer this question, the selected points of the jacket structure in Fig. 6 were studied, namely the Y- and K-connections below the transition piece. These points of the jacket support structure are chosen because they act as welded joints between piles and braces (see Fig. 6) and therefore the correct load analyses in this area is relevant for a reliable assessment of fatigue critical welded details [15].

A load spectrum for turbine loads with wind speeds between 10m/s and 25m/s including the corresponding hydrodynamic loads were simulated and analysed as load scenarios.

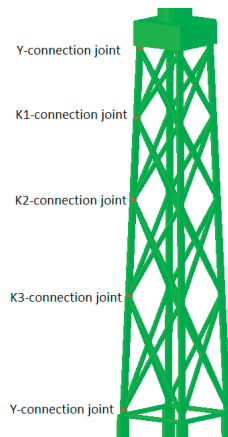


Fig. 6. Visualisation of Y- and K-connection points at the jacket structure (red marked).

The analyses of the shear forces and bending moments at the selected joints of the jacket support structure showed clearly differences between the fully coupled and uncoupled simulations. The magnitude reached up to the values of 25% for the mean shear forces and bending moments (see Fig. 7 and 8). The shear forces and bending moments of the uncoupled simulations have shown constantly higher loadings at the joints. During the analysis differences of the bending moments depending on the beam axis were significant. The bending moments of the uncoupled simulation around beam axis 1, which describes the bending in wind and wave direction, deviated stronger from the fully-coupled simulation results than the bending moments around beam axis 2 (perpendicular to beam axis 1). The differences reached up to approximately 5% higher deviations in wind and wave direction than perpendicular to it (compared Fig. 8). The comparison of the shear forces differences in loadings up to 25%. The maximum magnitudes

varied in the same ratio.

The simulations showed clearly a trend of deviations in the magnitudes of the jacket member loads and varying as a function of the mean wind speeds and wave heights. The higher the wind speeds and wave loadings the higher the differences between the fully-coupled and decoupled simulations results. The extreme loads on the jacket legs for a mean wind speed of 10m/s differed up to 17% and for the mean wind speeds near 15m/s that correspond to the overall maximum tower base overturning moment, the deviations reached 25%.

The significant differences in loading are also visible in the fatigue analysis. The computed damage equivalent loads show the same range of differences between the coupled and uncoupled analysis. The magnitude of the damage equivalent loads for the fully coupled simulations are approximately 17% to 25% lower than the damage equivalent loads for the decoupled simulations.

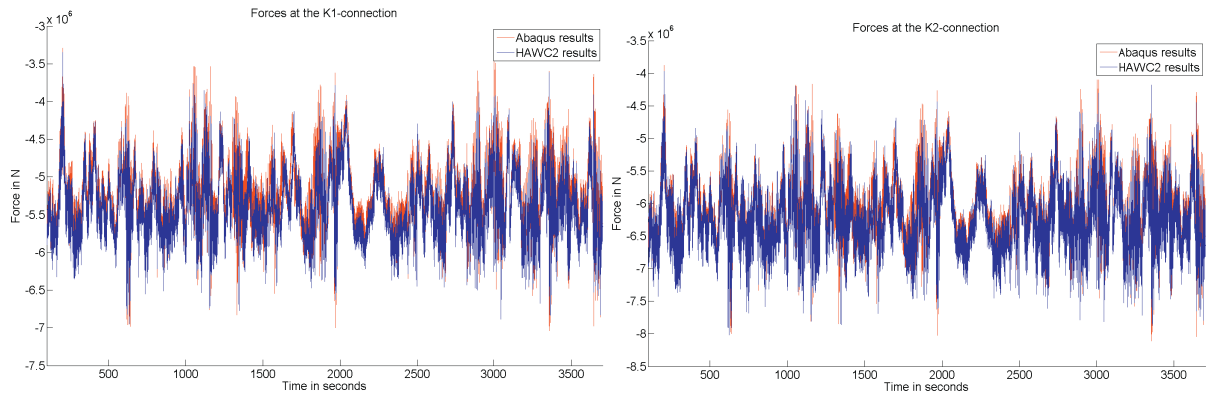


Fig. 7. Shear forces at selected parts of the jacket support structure.

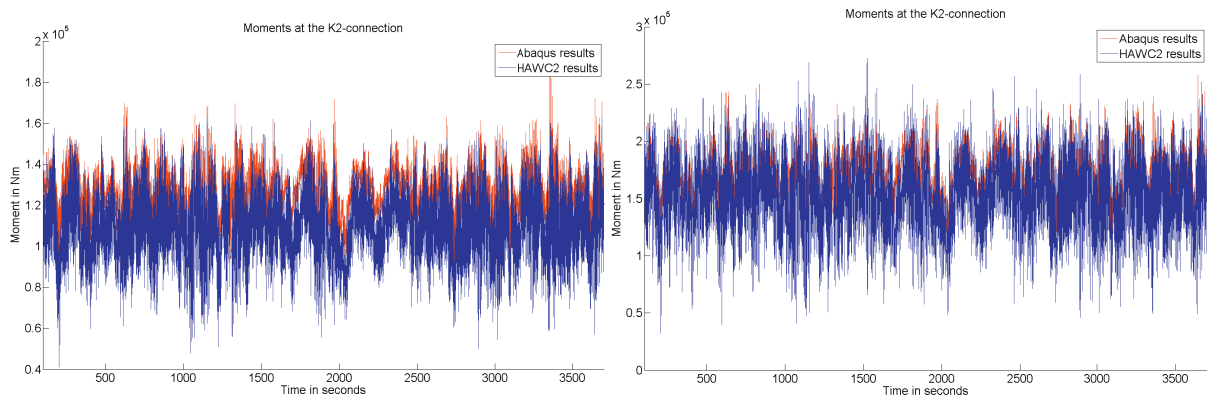


Fig. 8. Bending moment around the beam axis 1 and 2 at a selected part of the jacket support structure .

6. Conclusion

The comparison between the fully coupled simulation performed with HAWC2 and the uncoupled simulation shows reasonable match in the tower top displacements, and the mean jacket leg joints loads. However the extreme and fatigue loads on the jacket leg joints differed significantly between the two cases. The decoupled simulation method predicts higher extreme forces and moments in the Y- and K-connection joints of the jacket support structure. The fatigue load comparison shows the same trend that was shown for the shear forces and bending moments. The higher magnitudes predicted by the decoupled

method are the results of a significantly higher tower top displacement due to non-existing aeroelastic damping. The comparison shows clearly that aeroelastic and hydroelastic coupling can account for at least 25% of difference in loading on the jacket structure when compared to uncoupled simulations. The effects of fully coupled simulations can depict a bigger influence on larger and more flexible offshore wind turbines.

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